Field Evaluations of Concentrated Spray Applications of Microencapsulated Sex Pheromone for Codling Moth (Lepidoptera: Tortricidae)

A. L. KNIGHT,[1] T. L. LARSON,[2] K. KETNER,[2] R. HILTON,[3] AND L. HAWKINS[4]

Yakima Agricultural Research Laboratory, USDA–ARS, 5230 Konnowac Pass Rd., Wapato, WA 98951

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ABSTRACT The application of a microencapsulated (MEC) sex pheromone formulation (Checkmate CM-F) for codling moth, *Cydia pomonella* (L.), in low volume, concentrated sprays was evaluated in a series of small plot and grower trials in apple, *Malus domestica* Borkhausen, and pear, *Pyrus communis* L. Preliminary tests found that MEC sprays applied at 172–207 kilopascals in 12–23 liters/ha deposited the highest density of microcapsules per leaf. The addition of a latex sicker did not increase the deposition of microcapsules. Small plot tests in 2004 compared the effectiveness of two low-volume sprayers against a standard high-volume spray (926 liters/ha) applied at 1,379 kilopascals. Moth catches and fruit injury were significantly lower in plots treated with the low-volume sprays compared with plots treated with the standard sprayer. These results suggest that concentrating the MEC formulation increases the deposition of microcapsules and improves its effectiveness. Larger trials were conducted with a low-volume sprayer in 4-ha plots within commercial apple (2005–2006) and pear orchards (2005) paired with similar plots treated with hand-applied pheromone dispensers. Levels of fruit injury were not significantly different between pheromone treatments in any of the three tests. Moth catches, however, were significantly higher in the MEC- versus the dispenser-treated apple plots in 2005. No difference was found in the fruit injury levels in MEC-treated apple orchards in 2005 caused by irrigation method, but moth catches were significantly higher in overhead versus undertree orchards. The advantages and current limitations of using MEC sex pheromone sprays to supplement current grower's management strategies for codling moth is discussed.

KEY WORDS apple, pear, mating disruption, pest management, low volume

During the past decade, several formulations of microencapsulated (MEC) sex pheromones have been developed in North America to achieve mating disruption for a variety of lepidopteran pest species that attack deciduous tree fruits, such as codling moth, *Cydia pomonella* (L.), oriental fruit moth, *Grapholita molesta* (Busck), and tortricid leafrollers (Knight and Larsen 2004, Kovanci et al. 2004, Wins-Purdy et al. 2007). Interest in MEC formulations is generated by the products' ease of application and greater flexibility afforded to growers in targeting peak periods of pest activity and adjusting their application rates to match pest pressure than is possible with hand-applied dispensers (Campion 1976, Doane 1999). In addition, the use of MEC formulations has allowed pest managers to more easily treat crops with tall canopies, such as walnuts (Grant et al. 2004).

Unfortunately, the MEC technology is also characterized by several factors that limit its effectiveness, such as a typically sharp drop in emission rate after an initial large burst (Hall and Marrs 1989), rapid degradation of the capsule or active ingredient by UV light and oxygen (Färbert et al. 1997), variable rates of deposition depending on the epicuticular wax layer and degree of pubescence of various plant tissues that differ among crops and cultivars (Waldstein and Gut 2003, Knight et al. 2004), and variable rates of microcapsule dislodgement from treated plant surfaces, especially by water (Knight et al. 2004, Waldstein and Gut 2004).

The effectiveness of MEC formulations developed for different species has varied widely. For example, formulations for *G. molesta* have been largely successful in a number of tests conducted in North America (Trimble et al. 2004, Kovanci et al. 2005) and Australia (Il'chev et al. 2006), whereas field trials with formulations for codling moth have often been unsuccessful in reducing levels of fruit injury (Stelinski et al. 2007). Significant disruption of codling moth in sex pheromone–baited traps in treated versus untreated plots has been reported for only 1–2 wk in apple (Knight 2000), and up to 4 wk in walnuts (Grant et al. 2004). The longer period of trap suppression reported in

[1] Corresponding author, e-mail: aknight@yarl.ars.usda.gov.
[2] Suterra LLC, 213 SW Columbia St., Bend, OR 97702.
[3] Southern Oregon Research Center, 569 Hanley Rd., Central Point, OR 97502.
[4] Bear Creek Orchards, 2500 S. Pacific Hwy., Medford, OR 97501.

walnuts is hypothesized by these authors to be because of the greater shading provided in walnut versus apple orchards.

A number of efforts have attempted to improve the performance of microcapsules for codling moth by adjusting one or more application parameters. Surprisingly, increasing the application rate of microcapsules did not further reduce moth catches or levels of fruit injury (Stelinski et al. 2007). Another approach suggested for other pest species to reduce the cost of the program is to apply lower rates of pheromone more frequently during the season (Polavarapu et al. 2001, Il'chev et al. 2006). This approach is particularly compatible with pest management in orchards situated in wetter climates that must be treated with frequent fungicide applications during the season; however, the success of this approach for codling moth has been mixed (Stelinski et al. 2007). Laboratory studies have examined the use of stickers to increase the deposition and retention of microcapsules (Knight et al. 2004,Waldstein and Gut 2004), but under field conditions these increases have been minimal (Stelinski et al. 2007, Wins-Purdy et al. 2007). In contrast to the marginal improvements achieved with these various approaches, the addition of a MEC formulation of pear ester, ethyl (*E*,*Z*)-2,4-decadienoate, has significantly improved the performance of a sex pheromone formulation in limited testing in walnut orchards (Light and Knight 2005), but has not yet been tested in apple.

An additional parameter that may extend the life of MEC formulations could be the refinement of the spray application technique. Knight and Larsen (2004) reported that the effectiveness of a MEC formulation could be improved and significant reductions in male catch in virgin female-baited traps extended from 1 to 3 wk when applied in low-volume concentrated sprays (60 liters/ha) versus a dilute application made with an air blast sprayer. The low-volume spray deposited more capsules per leaf and also created a greater proportion of leaves with a high density of microcapsules (Knight and Larsen 2004). Subsequent flight tunnel studies with codling moth suggested that concentrating the microcapsules creates a short time period when the female's pheromone signal is camouflaged by the sprayed pheromone followed by a longer period where "false trail following" may be the major factor creating disruption (Stelinski et al. 2005). Moth contact with these "supercharged" leaves could also enhance the role of masking, antennal adaptation, or habituation of the central nervous system as suggested in studies with a MEC pheromone formulation for the obliquebanded leafroller, *Choristoneura rosaceana* (Harris) (Wins-Purdy et al. 2007).

The increased effectiveness achieved by concentrating the MEC formulation for codling moth suggests that this promising approach needs to be further evaluated and optimized. The initial work conducted with a low-volume MEC spray application was conducted in a single 4-wk trial in August 2000 using a customized sprayer applying 49.0 (AI) g codlemone in 46 liters/ha at 18 kilopascals (Knight and Larsen 2004). Since 2000, many cherry growers in the United States have adopted a low volume approach to apply an insectiicde mixed with an attractive bait (GF-120 NF Naturalyte Fruit Fly Bait; Dow AgroSciences, Indianapolis, IN) for control of *Rhagolitis* spp. fruit flies (Yee and Chapman 2005). This bait is applied using a fairly standardized sprayer apparatus (coined the GF-120 sprayer) mounted on an ATV vehicle (spray volume = 2–8 liters water/ha; spray pressure = 310–414 kilopascals). Because many cherry growers also produce apples and pears, the GF-120 sprayer was considered as an alternative platform to further develop the use of low-volume MEC sprays for codling moth.

Herein, we report a series of preliminary field trials that evaluated the importance of spray volume and pressure, nozzle height, and the addition of a latex sticker on the deposition of microcapsules using the Checkmate CM-F formulation. Small plot studies in apple, *Malus domestica* Borkhausen, were conducted to compare the efficacy of two low-volume spray approaches versus a standard air blast sprayer over an entire season. Larger trials were conducted in commercial apple and pear, *Pyrus communis* L., orchards to compare the seasonal effectiveness of a four to six application low-volume MEC spray program against the use of hand-applied dispensers.

Materials and Methods

Description of Sprayers. Four different sprayers were used to evaluate the deposition of microcapsules in the canopy of apple orchards. A Victair Mistifier (H. F. Hauff Co., Yakima, WA) sprayer with a 100-liter tank pulled by an ATV was used to apply the high-volume air blast MEC application in tests of microcapsule deposition. Seven spray nozzles (D2–D6 full cone tips with screens and swirl plates removed; TeeJet Technologies, Wheaton, IL) applied 10.4 liters/min at 689.5 kilopascals from only one side of the sprayer. Nozzle heights ranged from 1.08 to 1.70 m and were positioned at 45°. The speed of the ATV was maintained at 3.8 km/h to apply 935 liters/ha. A second type of high-volume sprayer (Rears Miniblast 300; Rears Mfg, Eugene, OR) pulled by a tractor was used in the 2004 field trial to apply the pheromone formulation in the same volume of water. This sprayer was driven at 2.3 km/h to apply 34.4 liters/min at 1,379 kilopascals through five nozzles (D5 and D7 tips) positioned at heights from 1.0 to 1.3 m on both sides of the sprayer.

Two types of low-volume sprayers were used in the deposition experiment. The first was the same boom sprayer described in Knight et al. (2004). It consisted of a 95-liter polyolefin tank mounted on a four-wheel drive ATV. The sprayer was rigged with an adjustable vertical spray boom outfitted with two flat fan nozzles (no. 2404; TeeJet Technologies). Nozzles were positioned on the boom at a height of 3.1 m, and sprays were applied at a 30° angle. The two nozzles together deliver a spray volume of 2.79 liters/min at 172 kilopascals. The second low-volume sprayer (GF-120) was also mounted on an ATV and used a similar spray tank, but nozzles (D3 tips with screen and swirl plates removed) were mounted lower on the sprayer (1.6 m from the ground) and angled at 45°. Sprays were applied at a rate of 1.6 liters/min at 207 kilopascals.

Evaluations of Spray Parameters. Two studies were conducted to evaluate the deposition of microcapsules when applied by different sprayers using different nozzles, in different spray volumes, and when combined with a spray adjuvant. Studies were conducted within a 4-ha orchard (35-yr-old interplanting of 'Delicious' and 'Golden Delicious') situated near Moxee, WA (46.6° N, 120.3° W). Mean (SE) tree height was 4.3 (0.1) m, with trees planted at a density of 450/ha. An experimental formulation of Checkmate CM-F was used in all of these tests. The formulation contained 15.8% codlemone with the addition of 0.11% of a fluorescent material ("Dye-Lite"; Tracer Products, Westbury, NY) to allow microcapsules to be easily counted on leaf surfaces. In each experiment, flagged plots (3 orchard rows by 50 m) were sprayed with pheromone at a rate of 24.7 (AI) g/ha. Nozzles on both low-volume sprayers were adjusted to aim the spray deposit at a height of 3.0–3.6 m in the canopy. The density of fluorescent microcapsules per leaf was sampled after all spray treatments by collecting five leaves from 10 trees in each replicate from two approximate heights (2.2 and 3.2 m) along the sprayed edge of the canopy. Leaves were collected 1–2 h after spraying from each canopy position within each plot. Microcapsules on both leaf surfaces were counted under an UV light in the laboratory (Black-Ray Long Wave UV Lamp; Ultra-Violet Products, San Gabriel, CA).

The first experiment examined whether adding the adjuvant, Bond (Loveland Industries, Greeley, CO), to Checkmate CM-F could increase the deposition of microcapsules. Bond, a 45.0% (AI) latex spreader sticker with a proprietary surfactant deposition agent, was added at a concentration of 0.06%. Pheromone sprays were applied using the boom sprayer at 46.9 liters/ha on four dates during 2003: 12, 13, 20, and 21 October.

A second experiment compared the microcapsule deposition with the two low-volume sprayers each applying the MEC pheromone at two spray volumes. Spray volume with the boom sprayer was adjusted by controlling the speed of the ATV at either 6.3 or 12.7 km/h to deliver 46.9 or 23.4 liters/ha; with the GF-120 sprayer, the ATV was driven at either 7.4 or 14.7 km/h to deliver 23.4 or 11.7 liters/ha. Studies with each sprayer were replicated on four dates during 2004: 12 and 18 May, 4 June, and 8 September.

Small Plot Evaluations. Replicated (n = 5) plots (0.3 ha) were established in two adjacent Moxee, WA, orchards (20 ha) during 2004. Plots were separated by 10-m untreated borders. Replicates of four treatments were randomly assigned among the plots. Checkmate CM-F (14.4% codlemone) was applied at 24.7 (AI) g with three different sprayers that were previously described: high-volume rears, low-volume boom, and low-volume GF-120. Spray volumes differed between the two low-volume sprayers: 23.4 and 11.7 liters/ha with the boom and GF-120 sprayers, respectively. The fourth treatment was an untreated control. Plots were monitored with two traps baited with either a sex pheromone lure (Pherocon L2; Trécé Adair, OK) or a pear ester lure (Pherocon CM-DA). Moth catch data were summarized for each moth flight based on the assumption that the start of the second moth flight occurs after the accumulation of 445 DD above a lower threshold of 10°C after the start of sustained moth flight (Biofix) on 3 May (Knight 2007a). Checkmate CM-F was sprayed on 3 and 24 May, 15 June, 14 July, and 4–6 and 18–19 August. Fruit injury by codling moth was assessed on 9–12 July by picking 90 fruit from 10 trees in the center area of each plot and again by picking 60 fruit from 20 trees in the same area of each plot on 29–31 August. All plots were treated during the season with two applications of a low rate (560 [AI] g/ha) of azinphosmethyl (Bayer CropScience, Research Triangle Park, NC). Fruit injury was assessed similarly in a small plot (0.1 ha) of unsprayed trees planted 50 m east of the orchard to provide a reference of pest pressure surrounding the orchard plots. These descriptive data were not used in the subsequent analyses.

Apple and Pear Orchard Trials. Trials were established in 2005 in eight 20-acre apple orchards situated near Brewster, WA (48° N, 119° W). The major cultivars in orchards included 'Delicious', 'Gala', 'Fuji', and 'Granny Smith'. Orchards were randomly subdivided into two plots, and one plot was treated with Isomate-C PLUS at 750 dispensers/ha and the other plot received five low-volume (11.7 liters/ha) spray applications of Checkmate CM-F (24.7 [AI] g/ha) applied every 4 wk starting on 2–7 May. Isomate-C PLUS dispensers were loaded with 182.3 (AI) mg of a 60:33:7 blend of (E, E)-8–10-dodecadien-1-ol (codlemone), dodecan-1-ol (12:OH), and tetradecan-1-ol (14:OH).

MEC sprays were applied by the grower, and several problems were reported on the first two application dates because of clogged screens and nozzles. After the second spray application, sprayers were always cleaned after each use. The cleaning protocol started with the addition of 2 liters of denatured alcohol to the empty tank, and the ATV was rocked side-to-side to coat the inside walls of the tank. Clean water (8 liters) was added to the tank and the sprayer was operated for 5 min. The remaining material in the tank was drained, and 8 liters of water was added, and the sprayer was again run for 5 min. The sprayer was cleaned with a final water rinse, and its contents were drained.

Orchard plots were monitored with two delta-shaped traps baited with a high load sex pheromone dispenser (Biolure CM 10x; Suterra LLC, Bend OR). Traps were checked every 2 wk during the season after the establishment of Biofix on 2 May. Moth catches were accumulated for each moth flight. Lures were replaced after 8 wk, and liners were replaced at each trap check. Orchards were monitored for fruit injury at midseason on 12–13 July and again on 7–9 September. The exposed surfaces of 1,200 fruits were visually checked from the ground (60 fruits on 20 trees) for codling moth injury, and this sample was scored as 600 total fruits. All orchards were also sprayed by the grower with supplemental applications of insecticides during the season (two to four sprays of organophosphates, insect growth regulators and neonicotinyls). The same sprays were applied across all paired blocks.

Similar commercial field tests were conducted in pear orchards in Medford, OR, during 2005. Six 'Comice' orchards were randomly divided into plots receiving either four low-volume applications of Checkmate CM-F (24.7 [AI] g/ha) or were treated with one of two different types of hand-applied dispensers at a rate of 500/ha. The grower applied all MEC sprays, and no problems with the sprayer occurred during the season. Three orchards were treated with Isomate-C TT twin-tube polyethylene dispensers loaded with 382.4 mg of a 53:30:6 blend of codlemone, 12:OH, and 14:OH, with 11.3% other ingredients. The other three orchards were treated with the solid laminate Disrupt CM-Xtra dispensers (Hercon Environmental, Emigsville, PA) loaded with 180.0 mg of codlemone (7.45% [AI]). Dispensers were applied in all orchards in mid-April. MEC sprays were applied on 19 April, 13 May, 13 June, and 14 July. The paired plots within each orchard were treated similarly with three to four insecticide applications during the season, including granulosis virus, IGRs, neonicotinyls, and spinosyns. Orchards were monitored with delta-shaped traps baited with three types of lures: a pheromone lure (Biolure CM 10X; Suterra), a pear ester lure (Pherocon CM-DA; Trécé), and a combination pheromone and pear ester lure (Pherocon CM-DA COMBO; Trécé). Traps were checked weekly, and lures were replaced after 8 wk. Moth catch data before 29 June and after 24 June were summarized as first and second moth flight, respectively. Fruit were sampled for codling moth injury in mid-August by picking 500 fruits per block and carefully checking the calyx of each fruit for frass.

Field trials in apple were repeated in 2006 in six orchards situated near Brewster, WA. All orchards were irrigated with undertree systems. Orchards were again split into 4-ha plots and treated with either Checkmate CM-F (24.7 [AI] g/ha) or 1,000 Isomate-C PLUS dispensers/ha. Five applications of Checkmate CM-F were made on 5 and 31 May, 21 June, 18 July, and 15 August. All MEC treatments were applied by our technical staff, and no problems with the sprayer occurred during the season. Two delta-shaped traps baited with the Biolure 10× lure were placed 50 m apart in each plot in early May. Traps were checked weekly, and lures were replaced after 8 wk. Biofix was established as 5 May, and moth counts through the 30 June sample were accumulated for first flight and from 7 July to 31 August as the second moth flight. Fruit injury was sampled on 12 July and 25 August. In both samples, fruits were visually sampled from the ground by checking half of the surface of 1,200 fruits (60 fruits from 20 trees) per plot. All orchards received a full insecticide spray program (four to six applications) with the same classes of insecticides used in 2005, and all paired plots were treated similarly.

Data Analysis. All data sets were subjected to the Shapiro-Wilk normality test to examine if the standardized residuals conformed to a normal distribution (Analytical Software 2003). If the hypothesis of a normal distribution was rejected, the data were transformed before further analysis. Moth counts per trap and numbers of microcapsules per leaf were transformed with either square root $(x + 0.5)$ or $\log(x + 1)$, and proportional data were transformed with arcsine (square root [x]). The density of microcapsules deposited on leaves by various sprayers was evaluated with a three-way analysis of variance (ANOVA) with sprayer, location within the canopy and leaf surface as the main factors (Analytical Software 2003). Moth catches in traps baited with two types of lures and percent fruit injury at mid-season and before harvest across three pheromone treatments and an untreated control in 2004 were evaluated with a one-way ANOVA. A two-way ANOVA was used to evaluate cumulative moth catch and percent fruit injury at the end of each of the two moth flights in the 2005 apple study with pheromone treatments and irrigation system as the main factors. A two-way ANOVA was also used to evaluate moth catch across pheromone treatments in traps baited with three different lures in pear orchards during 2005. Interaction terms, when there was more than one main factor, were included in the models for all ANOVAs. Linear contrasts were used to examine differences in the model if a significant interaction occurred. Significant means in ANOVAs were separated with Tukey's method ($P < 0.05$) (Analytical Software 2003). Paired *t*-tests were used to compare the cumulative moth catches and percent fruit injury between the two pheromone treatments for each moth flight in the studies conducted in apple in 2006.

Results

Evaluations of Spray Parameters. The addition of 0.06% Bond to the experimental formulation of Checkmate CM-F did not significantly increase the deposition of microcapsules within the canopy (Table 1). Interestingly, neither canopy height nor leaf surface were significant factors affecting the density of microcapsules. However, the interaction term canopy height × leaf surface was significant in the model because more capsules were deposited on the top of leaves lower in the canopy, whereas higher in the canopy, more capsules were deposited on the underside of leaves.

The GF-120 and boom sprayers deposited a variable number of microcapsules on leaves as a function of spray volume, canopy height, and leaf surface (Table 2). The two spray volumes applied by the GF-120 sprayer deposited similar number of microcapsules, but the lower spray volume deposited significantly more microcapsules than either spray applied with the boom sprayer. In general, all sprayers deposited more microcapsules higher in the canopy. However, the interaction term sprayer × canopy height was significant in the model because sprayer differences de-

Table 1. Mean (SE) density of microcapsules deposited following the application of an experimental Checkmate CM-F formulation (24.7 [AI] g/ha) applied with the GF-120 sprayer in 11.7 liters/ha combined with or without the latex sticker, Bond, at 0.06%

Sticker	Lower canopy		Upper canopy	
	Top of leaf	Underside of leaf	Top of leaf	Underside of leaf
Bond	6.0 (1.1)	2.5 (0.8)	3.4 (0.7)	6.5 (0.4)
None	4.3 (0.6)	1.4 (0.4)	2.3 (0.2)	6.2 (1.9)
Three-way ANOVA		*F*-value	*P* value	
$\text{Sticker}_{df = 1,24}$		2.70	0.11	
$\text{Canopy height}_{df = 1,24}$		2.76	0.11	
$\text{Leaf surface}_{df = 1,24}$		0.04	0.83	
$\text{Sticker} \times \text{canopy ht}_{df = 1,24}$		0.30	0.59	
$\text{Sticker} \times \text{leaf surface}_{df = 1,24}$		0.29	0.59	
$\text{Canopy height} \times \text{leaf surface}_{df = 1,24}$		26.72	<0.0001	
$\text{Sticker} \times \text{canopy height} \times \text{leaf surface}_{df = 1,24}$		0.01	0.92	

pended on canopy height. Leaf surface was not a significant factor affecting microcapsule density, and the interaction term sprayer × leaf surface was also not significant in the model. Similar to the previous study evaluating the use of a spray adjuvant, the interaction term canopy height × leaf surface was significant in the model.

Small Plot Evaluations. Significant differences were found in the cumulative moth catches in traps baited with two different lures during both moth flight periods and for percent fruit injury at both mid-season and before harvest (Table 3). Moth catches in sex pheromone–baited traps were significantly lower in all pheromone treatments compared with the untreated control in both flights. No difference was found in moth catches in sex pheromone–baited traps among the pheromone treatments in the first flight, but in the second flight, moth catch was significantly lower in the GF-120 treatment compared with the air blast spray treatment. The moth catches with the boom sprayer in the second moth flight period were intermediate. Moth catches in pear ester–baited traps during the first flight varied significantly among treatments with higher counts in the untreated control than either low-volume sprayer treatment. Counts in pear ester–baited traps in plots sprayed with the air blast sprayer were intermediate. Moth catches in pear ester–baited traps in the second flight were not significantly different among treatments. The numbers of female moths caught in the pear ester–baited traps were not significantly different among treatments during either flight period. Percent fruit injury was significantly higher in the untreated control than the two low-volume spray treatments at both mid-season and before harvest (Table 3). Mid-season levels of injury in the air blast treatment were intermediate at mid-season and not significantly different from the low-volume boom sprayer treatment before harvest. Percent fruit injury was significantly lower in plots treated with the GF-120 versus the air blast sprayer before harvest. Percent fruit injury in the adjacent, unsprayed reference plot was 6.2 and 64.0% at mid-season and preharvest, respectively.

Six spray applications of Checkmate CM-F were made during the 2004 season with spray intervals of 2–4 wk (Fig. 1). Spray intervals were dictated by our effort to maintain the effectiveness of the air blast treatment in suppressing moth catches relative to the untreated control. Early in the season, suppressing moth catch >70% was only possible for 2 wk with the air blast treatment, whereas later in the season, suppression was never higher than 60–70% despite the application of four additional sprays (Fig. 1). In particular, moth catches in the air blast and untreated

Table 2. Mean (SE) density of microcapsules deposited following the application of an experimental Checkmate CM-F formulation (24.7 [AI] g/ha) applied with two low-volume sprayers at two spray volumes

Sprayer, water volume	Lower canopy		Upper canopy	
	Top of leaf	Underside of leaf	Top of leaf	Underside of leaf
Low-volume boom (46.9 liters/ha	3.1 (0.6)	2.5 (0.9)	2.0 (0.5)	5.1 (0.8)
Low-volume boom (23.4 liters/ha)	3.2 (0.6)	1.3 (0.8)	5.8 (1.2)	8.4 (0.9)
Low-volume GF-120 (23.4 liters/ha)	5.2 (0.4)	2.3 (0.8)	3.8 (1.1)	11.0 (1.3)
Low-vol GF-120 (11.7 liters/ha)	9.2 (1.1)	3.6 (1.3)	4.7 (0.4)	9.7 (1.3)
Three-way ANOVA		*F*-value	*P* value	
$\text{Sprayer}_{df = 3,48}$		9.69	<0.0001	
$\text{Canopy height}_{df = 1,48}$		28.43	<0.0001	
$\text{Leaf surface}_{df = 1,48}$		1.03	0.32	
$\text{Sprayer} \times \text{canopy height}_{df = 3,48}$		5.03	<0.01	
$\text{Sprayer} \times \text{leaf surface}_{df = 3,48}$		1.22	0.31	
$\text{Canopy height} \times \text{leaf surface}_{df = 1,48}$		57.83	<0.0001	
$\text{Sprayer} \times \text{canopy height} \times \text{leaf surface}_{df = 3,48}$		2.07	0.11	

Table 3. Comparison of moth catches and codling moth injury in 0.3-ha plots of apple treated with six applications of Checkmate CM-F at a rate of 24.7 (AI) g with either an air blast sprayer (926 liters/ha), a low-volume boom sprayer (23.4 liters/ha), or a low-vol GF-120 sprayer (11.7 liters/ha), n = 5, Moxee, WA, 2004

Treatment	Mean (SE) total moth catch per trap						Mean (SE) percent fruit injury	
	First flight			Second flight				
	Pheromone	Pear ester	Pear ester (females only)[a]	Pheromone	Pear ester	Pear ester (females only)[a]	Mid-season	Pre-harvest
High-volume air blast sprayer	18.5 (4.7)b	15.5 (3.5)ab	4.5 (1.1)	82.3 (21.6)b	24.1 (3.1)	14.2 (1.6)	4.9 (2.2)ab	8.7 (2.3)b
Low-volume boom sprayer	14.0 (5.9)b	7.9 (0.8)b	3.1 (0.7)	38.9 (16.0)bc	10.1 (3.4)	5.8 (2.3)	1.5 (0.6)b	4.1 (1.5)bc
Low-volume GF-120 sprayer	7.4 (1.2)b	9.5 (3.4)b	4.0 (1.4)	17.5 (6.0)c	16.4 (7.5)	9.4 (5.9)	1.1 (0.3)b	3.3 (1.1)c
Untreated control	77.0 (6.9)a	25.4 (2.7)a	6.8 (0.5)	182.7 (25.8)a	29.9 (6.5)	17.6 (3.2)	9.2 (2.2)a	27.8 (8.7)a
ANOVA$_{df = 3,16}$	$F = 11.60$ $P < 0.001$	$F = 7.89$ $P < 0.01$	$F = 2.75$ $P = 0.08$	$F = 15.60$ $P < 0.0001$	$F = 2.52$ $P = 0.09$	$F = 2.10$ $P = 0.14$	$F = 5.37$ $P < 0.01$	$F = 6.21$ $P < 0.01$

Column means followed by a different letter were significantly different, $P < 0.05$, Tukey's method.
[a] Mean (SE) moth catches in parentheses are for female moths only.

plots were similar after the final spray. Moth catch suppression was greater in plots treated with the GF-120 than the boom sprayer, especially after the first week (Fig. 1).

The influence of precipitation on the suppression of moth catches in pheromone traps after each spray is shown in Fig. 1. Mean daily precipitation rates approaching 0.2 cm were associated with dramatic drops in suppression after the second and sixth application. Precipitation rates around 0.1 cm/d seemed to have strong affects against the air blast treatment. In contrast, little precipitation occurred over 4 wk after the third application, and the effectiveness of the air blast and low-volume boom sprayer were similar during this time period.

Apple and Pear Orchard Trials. Significant differences in cumulative moth catch for each flight period occurred during 2005 in apple plots treated with either Checkmate CM-F or Isomate-C Plus (Table 4). Moth catches were significantly higher in the Checkmate CM-F plots in both generations. The irrigation system used was also a significant factor affecting moth catch with higher moth counts in blocks with overhead irrigation. Furthermore, the interaction of pheromone treatment and the irrigation system used in orchards was significant as overhead irrigation affected moth catches in Checkmate CM-F– but not Isomate-C Plus–treated plots (Table 4). Irrigation was not significant factor affecting moth catches during the second moth flight. No significant difference in percent fruit injury

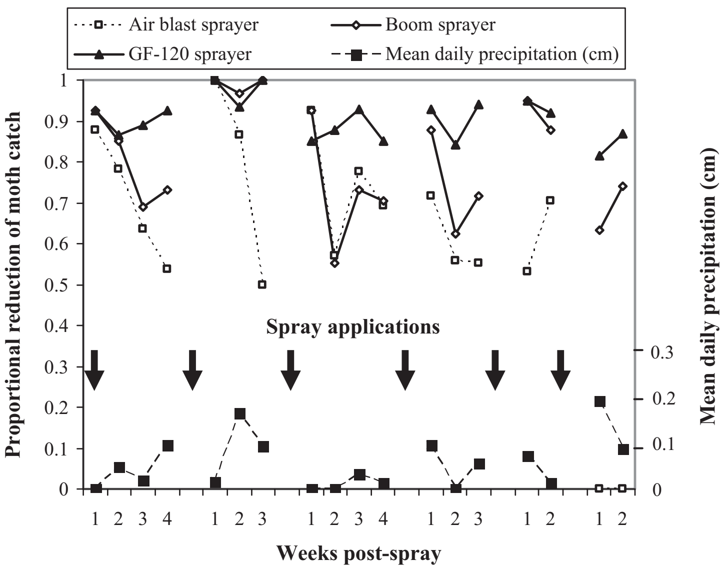

Fig. 1. The proportional reduction of moth catch in sex pheromone–baited traps in plots treated with the high volume air blast and low-volume boom, and GF-120 sprayers versus moth catch in untreated plots during 2004 (n = 5). Arrows designate spray dates. Data designated with solid squares are the mean daily precipitation (cm) measured during each time period during the study.

Table 4. Comparison of moth catches and codling moth injury in apple orchards treated with either five low-volume applications of 25 (AI) g Checkmate CM-F or the application of 750 Isomate-C Plus dispensers/ha

Treatment	Irrigation	Mean (SE) moth catch per trap		Mean (SE) percent fruit injury	
		First flight	Second flight	Mid-season	Preharvest
ULV	Undertree	32.8 (8.2)b	51.7 (22.6)	0.5 (0.3)	1.9 (0.7)
ULV	Overhead	113.8 (29.0)a	71.3 (20.2)	1.1 (0.3)	2.9 (0.5)
Isomate	Undertree	21.2 (4.5)b	20.2 (6.0)	0.2 (0.1)	2.8 (0.9)
Isomate	Overhead	21.8 (8.4)b	20.8 (9.9)	0.4 (0.2)	2.1 (0.2)
Two-way ANOVA$_{df = 1,12}$					
Treatment		$F = 15.96$	$F = 5.49$	$F = 3.58$	$F = 0.00$
		$P < 0.001$	$P < 0.05$	$P = 0.07$	$P = 0.99$
Irrigation		$F = 9.92$	$F = 0.34$	$F = 2.59$	$F = 0.05$
		$P < 0.01$	$P = 0.57$	$P = 0.12$	$P = 0.83$
Treatment × irrigation		$F = 9.61$	$F = 0.29$	$F = 0.51$	$F = 1.08$
		$P < 0.01$	$P = 0.59$	$P = 0.48$	$P = 0.31$

Data were grouped based on the irrigation system used in each orchard: overhead (n = 3) or undertree (n = 5), Brewster, WA, 2005. Column means followed by a different letter were significantly different, $P < 0.05$, linear contrasts.

occurred between pheromone treatment at either mid-season or preharvest nor was irrigation a significant factor affecting fruit injury (Table 4). Precipitation levels were low during 2005, with only 3.0 cm accumulating across 12 dates from Biofix date until 9 June. Subsequently, only 0.4 cm accumulated during the reminder of the season.

Moth catches in the pear orchards in Medford were much lower than in apple orchards in Brewster during 2005 (Table 5). Moth catches in traps baited with any of the three lure types were not significantly different in either generation in plots treated with hand-applied dispensers or Checkmate CM-F (Table 5). Levels of fruit injury were low in all pear orchards, with a mean (SE) percent injury of 0.01 (0.01) in the MEC-treated and 0.0 (0.0) percent injury in the hand-applied dispenser-treated plots. Levels of rainfall were somewhat higher in southern Oregon than northcentral Washington during 2005, with 7.8 cm recorded from the Biofix date to 7 June. After that date, only 0.8 cm was recorded over the rest of the season.

Moth catches in sex pheromone–baited traps were high in the first moth flight in all apple orchards in the 2006 Brewster study, but they did not differ between pheromone treatments (Table 6). Moth counts dropped by 10-fold in the second moth flight in all orchards during the second moth flight, and again, no difference was found across pheromone treatments. No fruit injury was found in orchards at mid-season, and low levels were found in both treatments before harvest (Table 6). Precipitation was heavier in Brewster during 2006 than the previous year, with 5.3 cm recorded across 10 dates from Biofix through 4 June. Similar to 2005, only 0.4 cm precipitation accumulated during the remainder of the season.

Discussion

Development of sprayable pheromone formulations for codling moth that could be a useful addition to the integrated pest management (IPM) programs developed in apple, pear, and walnut has been pur-

Table 5. Mean moth catches of codling moth in traps baited with three types of lures during each generation in pear orchards treated with either four applications of 25 (AI) g Checkmate CM-F or 500 pheromone dispensers/ha (n = 6), Medford, OR, 2005

Treatment[a]	Lure type	First flight		Second flight	
		Total moths	Female moths	Total moths	Female moths
Checkmate CM-F	Pheromone	1.8 (0.5)	—	1.4 (0.4)	—
Isomate-C tt	Pheromone	0.6 (0.2)	—	0.8 (0.6)	—
Checkmate CM-F	Pheromone/pear ester	4.7 (1.0)	2.0 (1.6)	6.9 (1.3)	1.2 (0.3)
Isomate-C tt	Pheromone/pear ester	3.7 (1.4)	0.3 (0.1)	5.5 (0.1)	0.7 (0.3)
Checkmate CM-F	Pear ester	0.9 (0.4)	0.3 (0.2)	0.7 (0.4)	0.3 (0.2)
Isomate-C tt	Pear ester	1.3 (0.6)	0.4 (0.3)	0.8 (0.3)	0.5 (0.2)
Two-way ANOVA					
Treatment$_{df = 1,30}$		$F = 1.27$	$F = 0.72$	$F = 1.21$	$F = 0.22$
		$P = 0.27$	$P = 0.41$	$P = 0.28$	$P = 0.65$
Lure type[a]		$F = 8.89$	$F = 0.81$	$F = 21.74$	$F = 4.56$
		$P < 0.001$	$P = 0.38$	$P < 0.0001$	$P < 0.05$
Treatment × lure type[a]		$F = 0.94$	$F = 1.35$	$F = 0.57$	$F = 2.80$
		$P = 0.40$	$P = 0.26$	$P = 0.57$	$P = 0.11$

Values are mean (SE) catch per trap.

[a] The degrees of freedom for the factors lure type and treatment × lure type in the ANOVAs for total moths and female moths were 2,30 and 1,20, respectively.

Table 6. Comparison of moth catches and codling moth injury in apple orchard blocks treated with either five applications of 25 (AI) g of Checkmate CM-F or 1,000 Isomate-C Plus dispensers/ha (n = 6), Brewster, WA, 2006

Treatment	Mean (SE) no. moths caught per trap		Mean (SE) % fruit injury[a]	
	First flight	Second flight	Mid-season	Preharvest
Checkmate CM-F	41.0 (17.6)	3.2 (1.5)	0.00	0.04 (0.02)
Isomate-C Plus	27.5 (6.7)	4.1 (1.1)	0.00	0.04 (0.02)
Paired t-test	t = 2.33 P = 0.07	t = −0.83 P = 0.44		

[a] No statistical tests were conducted for fruit injury.

sued for nearly 30 yr (Moffitt 1978). Unfortunately, there have been a number of physical and chemical problems that have impeded the development of an effective MEC formulation, such as temporal aspects of their emission profile and structural integrity of the microcapsules (Weatherston 1990), as well as difficulty in protecting the chemical stability of the sex pheromone (Millar 1995). Clearly, further improvements that can extend and expand the performance of MEC formulations would be useful. Meanwhile, our efforts to increase the initial deposition and the retention of microcapsules have directly improved the performance of the MEC formulation (Knight and Larsen 2004, Knight et al. 2004). Results reported here refine this work and further our understanding of the potential and limitations associated with using MEC formulations to manage codling moth.

Adoption of the GF-120 sprayer mounted on an ATV has allowed us to further concentrate the spray formulation and the use of lower spray volumes has significantly increased the deposition of microcapsules and the performance of the MEC formulation. Reducing the spray volume allows growers to further reduce their application cost. Mounting the nozzles lower on the GF-120 sprayer and increasing the spray angle also increased the relative deposition of microcapsules on the bottom versus the top surface of leaves. Microcapsules deposited on the underside of leaves are less likely to be dislodged by water (Knight et al. 2004) and are better protected from direct exposure to UV light (Hall and Marrs 1989).

Several studies have attempted to improve both the deposition and retention of microcapsules by adding various adjuvants. The density of microcapsules deposited on apple leaves in laboratory studies were doubled with the use of either a polyvinyl or latex sticker (Bond); however, only Bond increased the retention of microcapsules (2- to 4-fold) after a controlled precipitation event in the laboratory (Knight et al. 2004). Surprisingly, Bond did not increase microcapsule deposition in our field study, and we did not examine any possible affect on retention of microcapsules because of the rapid degradation of the fluorescence of the experimental formulation. A more indirect approach (moth catches in treated versus untreated plots) was used to evaluate a pine resin sticker added to a MEC formulation for codling moth (Stelinski et al. 2007). No improvement in suppressing moth catches by adding the sticker to the MEC formulation was noted in this study. Similarly, the addition of horticultural mineral oil did not improve or extend the suppression of moth catches by another MEC formulation (Wins-Purdy et al. 2007).

The compatibility of applying MEC formulations with other pesticides has been a major factor used to promote their use (Doane 1999). However, the potential chemical and physical interactions of the MEC formulations with various pesticides and adjuvants commonly used in tree fruits and nuts have not been reported. Not unexpectedly, sprays of kaolin clay, used by growers to protect fruit finish and reduce sunburn (Wünsche et al. 2004), when applied after a MEC spray, reduced the emission rate of pheromone from the microcapsules by 22% (Ketner 2002). More study is needed to assess the temporal and spatial compatibility of MEC pheromones with spray materials applied as fruit coatings before their joint use is precluded.

The effectiveness of the MEC pheromone was strongly influenced by both the orchard's type of irrigation and the occurrence of precipitation. The use of MEC pheromone sprays within orchards with overhead irrigation should be maximized through careful coordination of grower's irrigation and spray scheduling, i.e., spray after the completion of an irrigation cycle. The use of MEC sprays early in the season within the arid fruit and nut production area in western North America is somewhat problematic because of frequent periods of precipitation during the first 30–40 d after the start of moth flight. However, it was encouraging that suppression of moth catches in plots treated with the low-volume applications seemed to be less affected by precipitation than in similar plots treated with the air blast sprayer.

No significant difference in fruit injury occurred between the MEC- and hand-applied dispenser plots in all three sets of field trials conducted in 2005 and 2006. However, levels of fruit injury were low in two of the three sets of trials, and all plots were sprayed with insecticides. Comparing the effectiveness of two or more sex pheromone formulations in commercial orchards is often difficult because of the grower's use of supplemental insecticides (Knight 2004). In addition, we were unable to include a nonpheromone treatment in these studies to assess the impact of the sex pheromone component.

Monitoring traps baited with high-load sex pheromone lures were used in our studies primarily to monitor the relative population densities of codling moth within plots but were also included to assess relative differences in disruption between sex pheromone treatments. Relatively high moth catches occurred in traps during the 2005 apple trial and were significantly higher in the MEC- versus the hand-applied dispenser treatment (irrespective of irrigation method) only during the second moth flight. These data may have resulted from the problems experienced by the grower applying the MEC sprays early in the season, which was also reflected by the somewhat higher mid-season levels of fruit injury in this treatment. However, despite catching 2.0- to 4.5-fold more moths per trap in the MEC-treated plots, levels of fruit injury were similar between the two pheromone treatments. Growers typically use moth catches in sex pheromone–baited traps to establish action thresholds (Knight and Light 2005), and the relatively higher counts recorded in the MEC- versus the hand-applied dispenser-treated plots could trigger additional prophylactic sprays. We hypothesize that the behavioral impact on male codling moth's orientation to traps in plots treated with 500–1,000 hand-applied dispensers/ha compared with low-volume MEC sprays could be fundamentally different (Judd et al. 2005, Stelinski et al. 2005, 2006). These results suggest that different action thresholds based on moth catches in sex pheromone–baited traps may be needed for MEC- versus hand-applied dispenser-treated orchards.

Program cost and ease of use are major factors affecting the adoption of any new technology. Seasonal programs using four to six applications of MEC pheromone would likely be much higher than grower's current cost with hand-applied dispensers, especially for growers using reduced rates of dispensers. The seasonal use of a MEC pheromone formulation in walnuts was reported to be five-fold higher than grower's current insecticide program (Stewart-Leslie 2003). The short residual effectiveness of MEC formulations and the uncertainty in predicting random events, such as precipitation, certainly hinder its adoption. The need to reapply the MEC formulation through the season without creating temporal periods when the orchard is not well protected is cumbersome for some growers and likely also limits its adoption. Finally, the difficulty in assessing the residual effectiveness of the MEC formulation during the season increases uncertainty and thus grower's risk.

Alternative strategies are available that can target the use of the MEC pheromone formulation for codling moth to supplement specific management needs in sex pheromone–treated orchards. For example, MEC sprays can be used to supplement the borders of orchards where codling moth pressure is generally the greatest (Knight 2007b). MEC pheromone sprays can also be used to increase disruption of moth behaviors during peak periods of activity within each generation. Finally, MEC pheromone sprays could be used at the end of the season to extend the effectiveness of various hand-applied dispensers (Kovanci et al. 2004).

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